

AD-A244 085



WL-TM-91-328

1

**PARTICLE RELAXATION DISTANCES
DOWNSTREAM OF NORMAL
AND OBLIQUE SHOCKS**



Maurice, M.S.

December 1991

DTIC
ELECTE
JAN 7 1992
S B D

Approved for public release; distribution unlimited.

92-00305



AERO-OPTIC INSTRUMENTATION GROUP
EXPERIMENTAL ENGINEERING BRANCH
AEROMECHANICS DIVISION
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6553

92 1 6 098

10 DEC 91

Particle Relaxation Distances Downstream of Normal
and Oblique Shocks

WU 24041321

Mark S. Maurice

WL/FIMN
Wright-Patterson AFB, OH 45433-6553

WL-TM-91-328

Approved for public release. Distribution is
unlimited.

A particle equation of motion is coupled with ideal, inviscid shock theory to predict the dynamic velocity bias of laser velocimetry seed within these flow regions. Dimensionless graphs of relaxation distances are presented as an aid for experimental design and data evaluation efforts.

Laser Velocimetry

Shock Wave

10

UNC

UNC

UNC

UL

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to **stay within the lines to meet optical scanning requirements.**

Block 1. Agency Use Only (Leave Blank)

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C - Contract	PR - Project
G - Grant	TA - Task
PE - Program Element	WU - Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Names(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. (If known)

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of ..., To be published in When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement.

Denote public availability or limitation. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR)

DOD - See DoDD 5230.24, "Distribution Statements on Technical Documents."

DOE - See authorities

NASA - See Handbook NHB 2200.2.

NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - DOD - Leave blank

DOE - DOE - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports

NASA - NASA - Leave blank

NTIS - NTIS - Leave blank.

Block 13. Abstract. Include a brief (Maximum 200 words) factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code (NTIS only).

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

Particle Relaxation Distances Downstream of Normal and Oblique Shocks

**Mark S. Maurice
Flight Dynamics Directorate
Wright Laboratory
Wright-Patterson AFB, Ohio**

Introduction

Laser Velocimetry (LV) is based on measuring the velocity of 'seed' particles within a flowfield. Consequently, the particles are assumed to follow fluid streamlines and to model the flowfield velocities. For several primary flow structures, however, such as shock waves, vortices, expansion turns, and turbulent eddies, seed particles do not always model the fluid. They can be centrifuged from vortices and expansion turns, and lag behind turbulent frequencies in both phase and amplitude. In the case of shock waves, the upstream momentum of a particle may be unaffected by the shock itself, relying on drag forces immediately downstream of the shock to slow the particle to the fluid velocity.

An example of particle lag downstream of a shock wave is shown in Fig. 1. In this experiment¹, LV measurements were made through the boundary layer at the vertex of a Mach 6 roughened plate - compression ramp model using polydispersed silicon oil as seed material. Following the velocity histograms from the freestream towards the plate, the outer measurement stations are above the separation shock, and show the high velocity and low turbulence intensity of the freestream. Just below the shock, only the smallest seed within the continuum of particle size has relaxed to the fluid velocity, smearing the lower velocity distribution of the histogram. Continuing into the boundary layer, particles are further downstream of the shock. Consequently, there is a gradual shift from particles remaining near the upstream velocity, towards relaxing to the downstream fluid velocity. The mean velocity and turbulence intensity statistics from this data both over-estimate the velocity and turbulence intensity of the fluid.

As an aid to the experimental design process and measurement analysis of LV data, a general

solution is presented for estimating the distance which LV seed travels before relaxing to the fluid velocity behind a normal or oblique shock.

Approach

Analytical approaches for quantifying particle lag behind shock waves are plentiful, extending back to the late 1960's and early 70's². More recently, Nichols³ extended the domain of the analysis by coupling a form of the particle equation of motion derived by Maxey and Riley⁴ with the drag law of Crowe⁵, which accounts for inertia, compressibility, heat transfer, and rarefaction effects from subsonic to hypersonic Mach numbers. The resulting equation set applied to the uniform, steady-state flow downstream of a shock wave can be written as:

$$\frac{d\vec{v}}{dt} = - \frac{3C_d}{4d} \frac{\rho_f}{\rho_p + \rho_f/2} (\vec{v} - \vec{u}) |\vec{v} - \vec{u}| + H_c \int_0^t \frac{d}{d\tau} \frac{(\vec{v} - \vec{u})}{(t - \tau)^{1/2}} d\tau \quad (1)$$

and

$$C_d = f(Re_R, M_R, T_p/T_f) \quad (2)$$

where v is the particle velocity, u is the fluid velocity, d is the particle diameter, f and p denote the fluid and particle respectively, R denotes relative conditions between the fluid and the particle, and H_c is the history integral coefficient.

The subsequent general solution to the equation of motion is found by numerical integration, neglecting the effects of the history integral. Although Nichols shows that the integral term can be important when the seed density is near or less than the fluid density, or when the particle relative acceleration is large compared to the particle relative velocity, the term itself is numerically unstable. Unlike the drag term, which dampens out numerical perturbations, perturbations within the numerically evaluated integral term were found to grow unbounded. Consequently, the contribution of the term was either negligible or inseparable from the accumulation of truncation and round-off errors.

This paper extends the utility of prior works by reducing the equation set to three independent similarity parameters, and then providing graphical results over a wide range of independent variables.

Results

A typical result of numerically integrated particle lag is shown in Fig. 2, which represents the velocity lag of various sized seed particles through a normal shock at the Mach 6 test conditions. In this case, the velocities of particles as a function of downstream distance from the normal shock are defined by the upstream Mach number, pressure and temperature, and the particle density and diameter. If the same coordinate system is applied to an oblique shock, the particle equation of motion becomes a coupled set for the two dimensions, and the shock angle also needs to be specified.

Although six parameters are required to define the problem, numerical solutions can be expressed in terms of the upstream normal Mach number, the particle Reynolds number, and the particle to fluid density ratio. First, note that the tangential velocity of the particle will remain constant behind the shock wave since the tangential velocity of the fluid does not change across the shock. Therefore, by orienting the axes to be normal and tangential to the oblique shock, the velocity lag normal to the shockwave is de-coupled from the constant tangential velocity. Numerical solutions are then one-dimensional with the shock angle and upstream Mach number replaced by the upstream normal Mach number.

$$M_{1n} = M_1 \sin(\theta) \quad (3)$$

The variable set is further reduced by dimensional analysis. By using Sutherland's viscosity law for closure and restricting the analysis to air, application of the Π theorem shows that the particle lag normal to the shock can be fully described in terms of four similarity parameters. The large number of solutions required to present results over the domain of the problem are generated using 4th order Runge-Kutta-Fehlberg (RKF) numerical integration. The particle equation of motion is stiff for small particle diameters; consequently, the RKF method is ideally suited to this case since it calculates the local stiffness of the equation at each time step and adjusts the step size accordingly.

For upstream normal Mach numbers up to 6.0, upstream particle Reynolds numbers from 3.2×10^4 to 3.2×10^5 , and for upstream density ratios from 10^1 to 10^7 , the downstream normal distance at which the particles relax to within three percent of the fluid velocity can be interpolated from Figs. 3. These curves are calculated for an upstream temperature of 300 K, however, the results do not vary greatly for other temperatures. For lower temperatures the

presented graphs are conservative, over-estimating the relaxation distance from 0 to 28 percent when the temperature is decreased to 50 K. For temperatures as high as 1000 K, the distance is under-estimated by less than 5 percent.

For fixed flowfield conditions, individual curves can be interpreted as the relaxation distance for seed of a specific density over a range of particle diameters. As the diameter is decreased towards a nominal particle Reynolds number of 1.0, the curves show a corresponding decrease in particle lag. As the diameter is decreased further, rarefaction effects cause the curves to level off towards a minimum value. Consequently, decreasing the particle diameter in order to shorten the relaxation distance will not be successful in this region. On the other hand, particle lag can be still be reduced by using less dense seed, since this corresponds to dropping to a lower curve.

For a constant upstream Reynolds number and density ratio, increasing the upstream Mach number increases the initial velocity ratio behind the shock, as well increasing the downstream fluid density and viscosity. For weak shocks, The higher initial velocity ratio causes the particle lag to increase rapidly from $x/d=0.0$ at Mach 1.0 towards a peak value at about Mach 1.1. Increasing the Mach number further shows that the higher downstream density and viscosity become dominant, causing the particle lag to decrease nearly linearly. Therefore, for Mach numbers between 1.0 and 1.1, the relaxation distance should be interpolated between $x/d=0.0$ and the graphical value at Mach 1.1. Relaxation distances for Mach numbers between 1.1 and 6.0 can be found by interpolating between the three graphs.

References

¹Maurice, M.S. and Seibert, G.L., "The LV Measured Turbulent Structure of Mach 6 Flow Over a Roughened Flat Plate With a Compression Ramp", AIAA Paper 89-2164, July 1989.

²Durst, F., Melling, A. and Whitelaw, J.H., Principles and Practice of Laser-Doppler Anemometry, Academic Press, London, 1976.

³Nichols, R.H., "The Effect of Particle Dynamics on Turbulence Measurements With a Laser Doppler Velocimeter", Ph.D. Dissertation, Dept. of Aerospace Engineering, The University of Tennessee, Knoxville, June 1986.

⁴Maxey, M.R. and Riley, J.J., "Equation of Motion for a Small Rigid Sphere in a Nonuniform

Flow", Physics of Fluids, Vol. 26, 1983.

⁵Crowe, C.T., "Drag Coefficient of Particles in a Rocket Nozzle", AIAA Journal, Vol. 5, May 1967, pp. 1021-1022.



Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

LV MEASURED AXIAL VELOCITY HISTOGRAMS

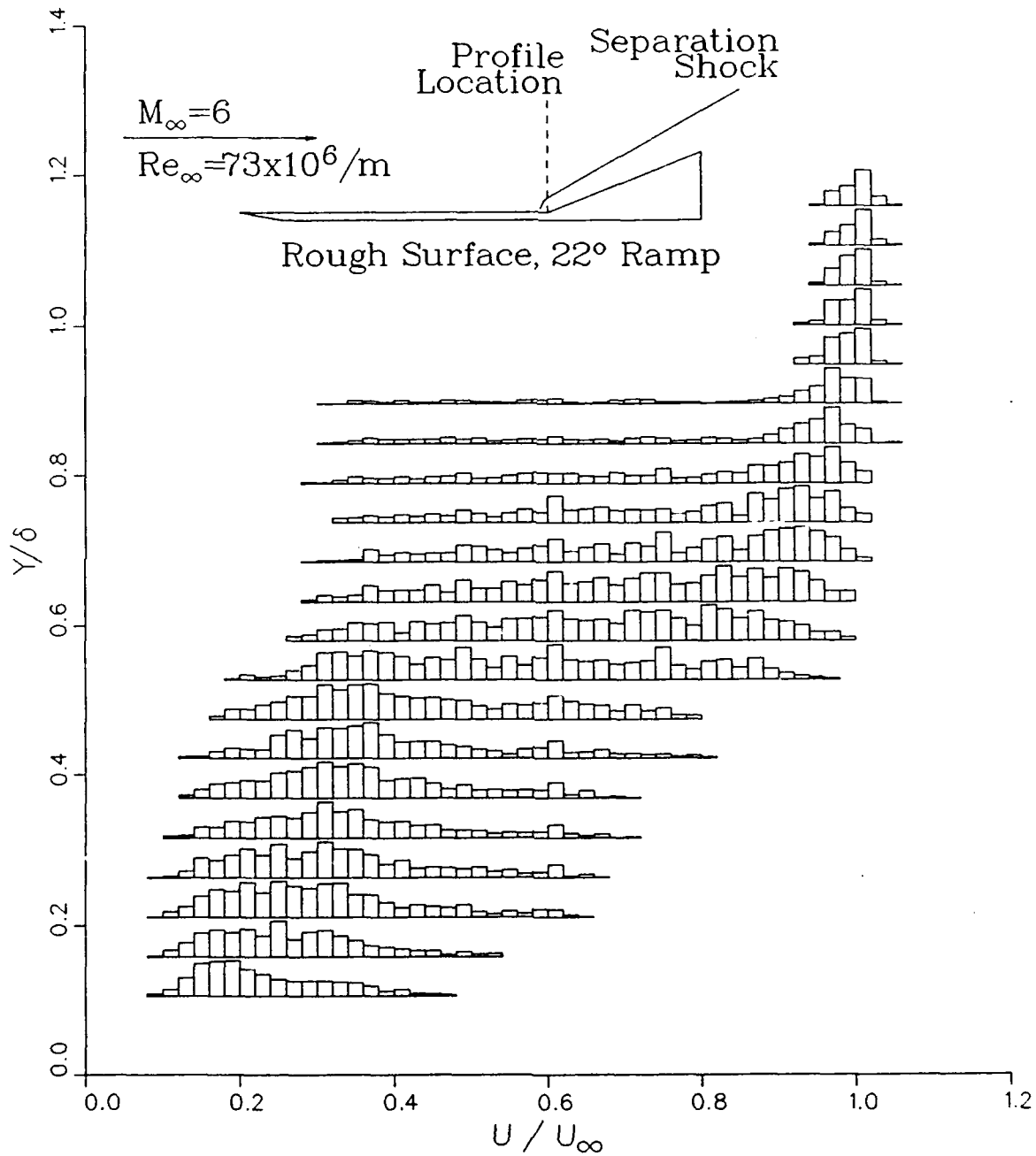


Fig. 1) Measured particle lag downstream of a shock.

PARTICLE LAG DOWNSTREAM OF A NORMAL SHOCK

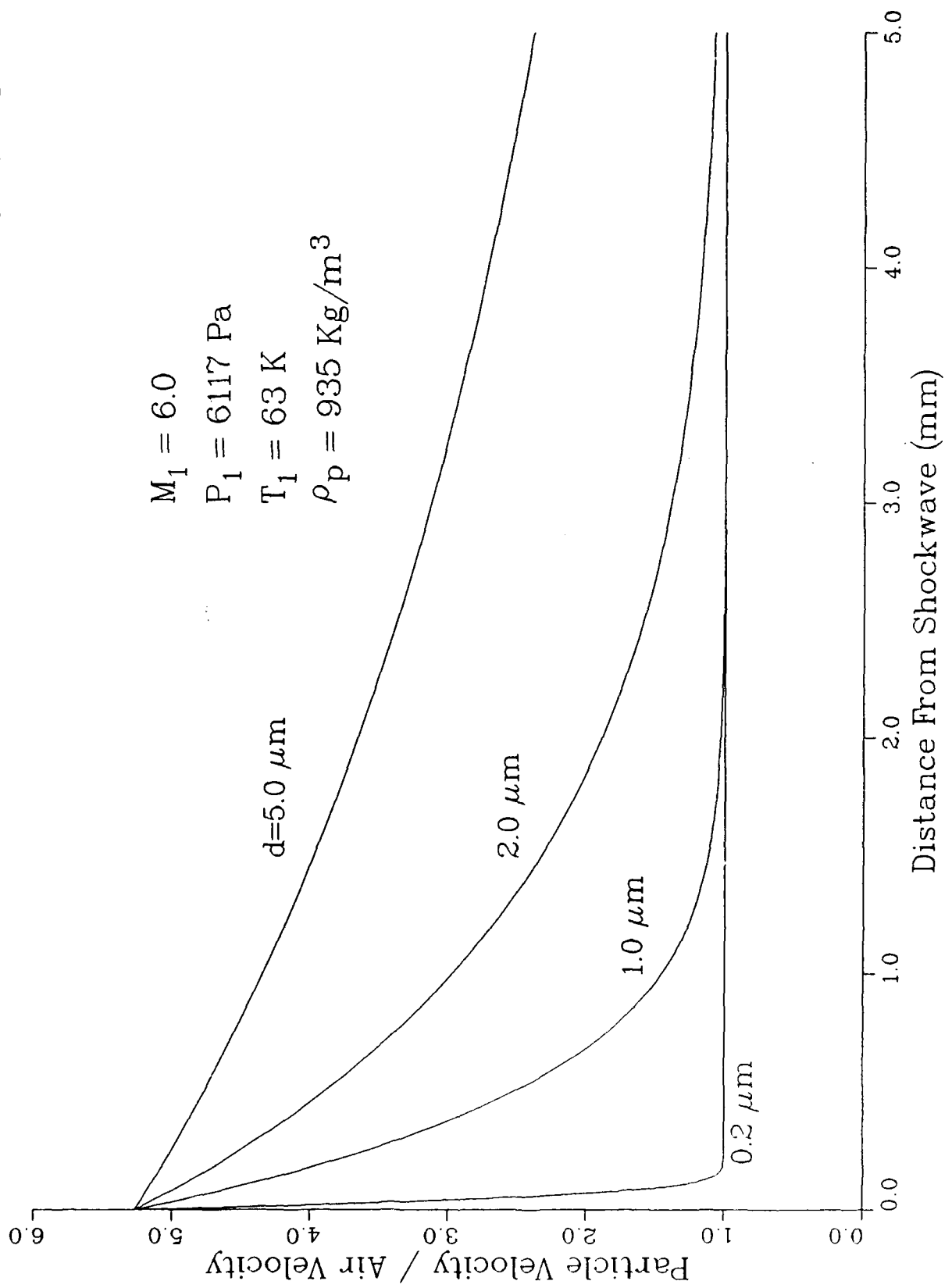


Fig. 2) Representative computational prediction of particle lag.

PARTICLE LOCATION FOR 3% VELOCITY BIAS

$M_{1n} = 1.1$

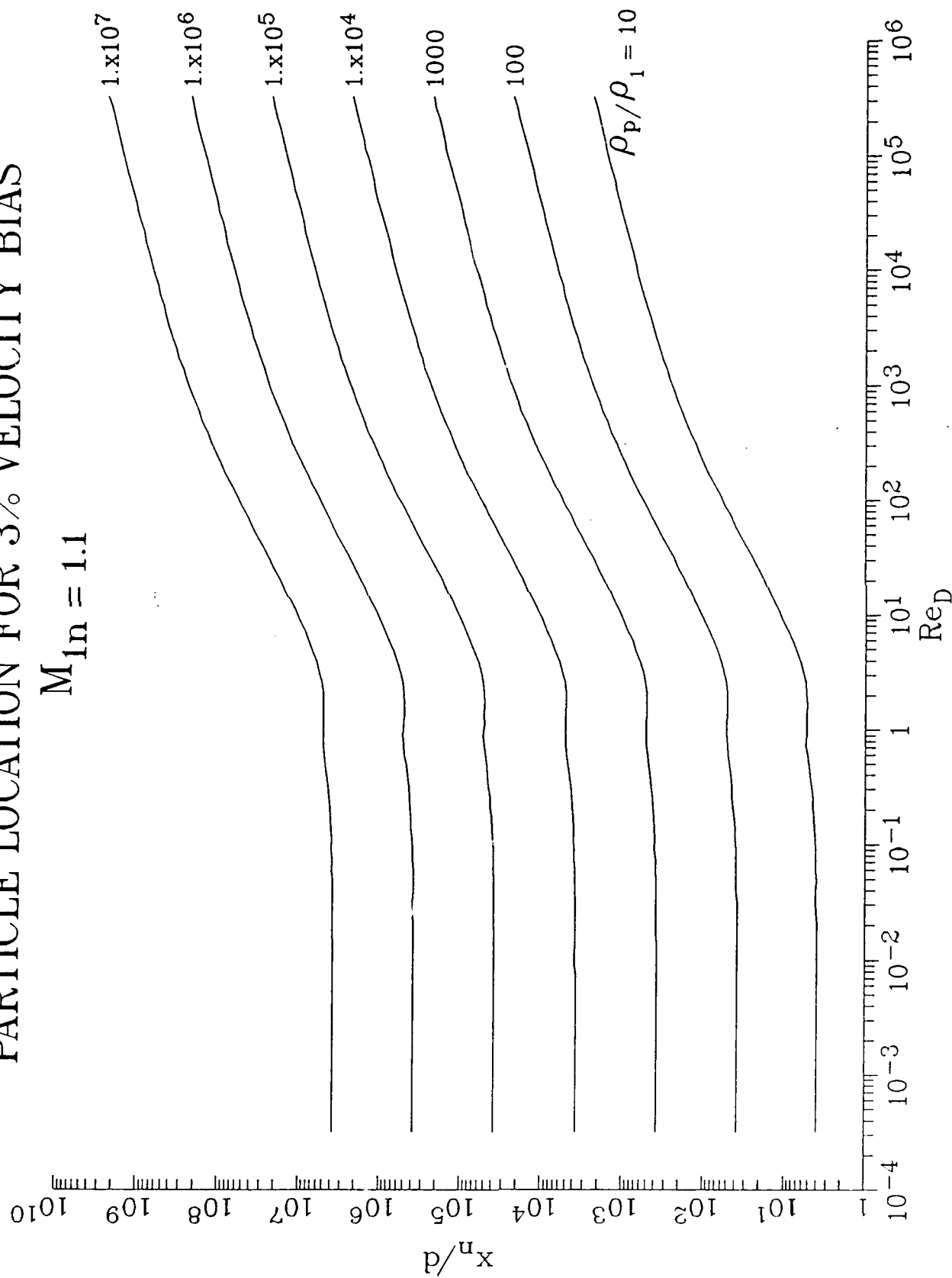


Fig. 3a) General results for an upstream normal Mach number of 1.1

PARTICLE LOCATION FOR 3% VELOCITY BIAS

$M_{1n} = 3.0$

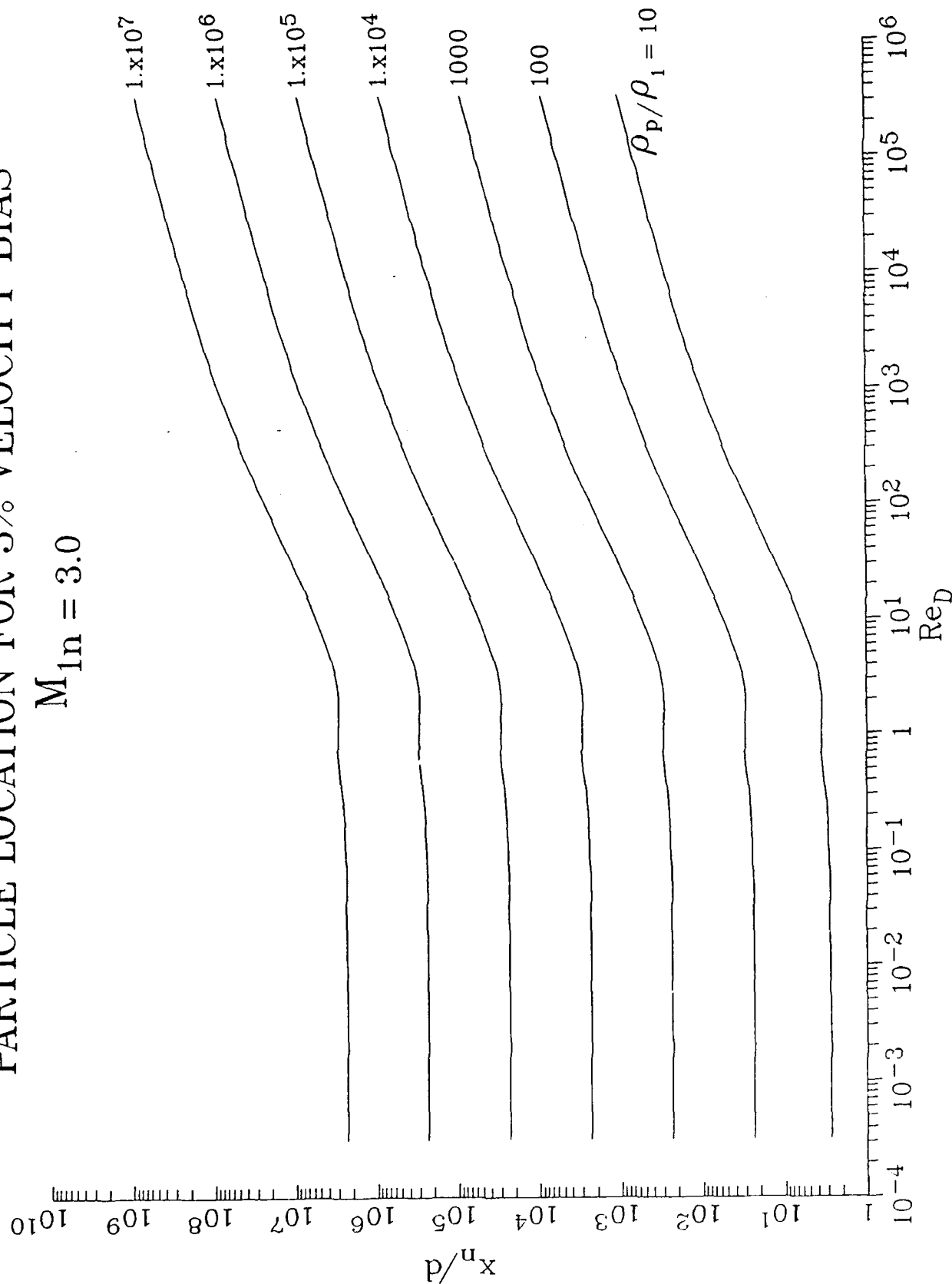


Fig. 3b) General results for an upstream normal Mach number of 3.0

PARTICLE LOCATION FOR 3% VELOCITY BIAS

$M_{1n} = 6.0$

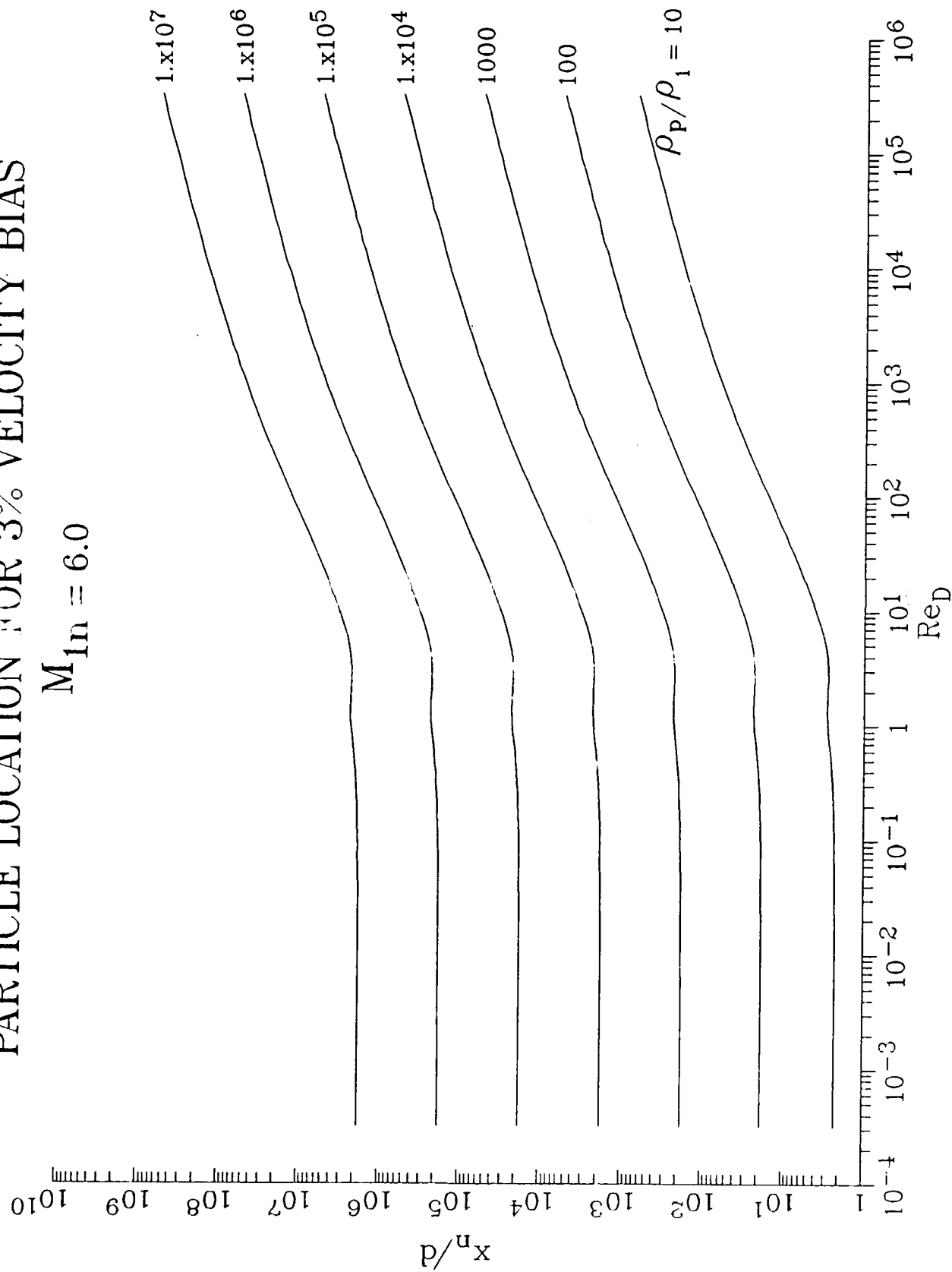


Fig. 3c) General results for an upstream normal Mach number of 6.0